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14. ABSTRACT

This paper presents the status and results from an ongoing development and flight test program that is investigating both reusable nanosat launch vehicles (RNLV), with an emphasis on fast turn-around operations, and early pathfinding for operationally responsive space. A related objective is enhancing the Technology Readiness Level of candidate launch vehicle technologies whenever they can be accommodated as complementary research experiments. The present program builds upon previous work that featured four flight tests (two conducted in a single day within 3.5 hours) with an earlier prototype RNLV first stage (the Prospector 7) that was developed under a Phase I SBIR sponsored by the Air Force Research Laboratory - Propulsion Directorate with support from the Air Force Space & Missile Systems Center. Recent work that falls under the scope of a follow-on Phase II SBIR contract has focused on developing a next-generation prototype RNLV first stage. The Phase II objective is to improve both the performance environment and operational fidelity of these flight tests, thereby bringing them closer to those anticipated for orbital missions. Milestones during the past two years have included horizontal static fire testing of a new 4.5 klbf-thrust LOX/ethanol first stage engine, vertical static fire testing of this engine with an interim test vehicle (the Prospector 8) and its initial flight demonstration, and integration and an initial static fire test attempt with the next prototype vehicle (the Prospector 9). Among the latter's most notable design features are two full-scale composite cryogenic propellant tanks. Final integration and operational preparations are gearing up to initiate low-altitude flight testing later this summer.

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Rapid Turn-Around Flight Testing of a Next-Generation Prototype RNLV (Preprint)

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This paper presents the status and results from an ongoing development and flight test program that is investigating both reusable nanosat launch vehicles (RNLV), with an emphasis on fast turn-around operations, and early pathfinding for operationally responsive space. A related objective is enhancing the Technology Readiness Level of candidate launch vehicle technologies whenever they can be accommodated as complementary research experiments. The present program builds upon previous work that featured four flight tests (two conducted in a single day within 3.5 hours) with an earlier prototype RNLV first stage (the Prospector 7) that was developed under a Phase I SBIR sponsored by the Air Force Research Laboratory - Propulsion Directorate with support from the Air Force Space & Missile Systems Center. Recent work that falls under the scope of a follow-on Phase II SBIR contract has focused on developing a next-generation prototype RNLV first stage. The Phase II objective is to improve both the performance environment and operational fidelity of these flight tests, thereby bringing them closer to those anticipated for orbital missions. Milestones during the past two years have included horizontal static fire testing of a new 4.5 klbf-thrust LOX/ethanol first stage engine, vertical static fire testing of this engine with an interim test vehicle (the Prospector 8) and its initial flight demonstration, and integration and an initial static fire test attempt with the next prototype vehicle (the Prospector 9). Among the latter's most notable design features are two full-scale composite cryogenic propellant tanks. Final integration and operational preparations are gearing up to initiate low-altitude flight testing later this summer.

I. Introduction

Focused research on a candidate Nanosat Launch Vehicle (NLV) capable of delivering on the order of 10 kg to low Earth orbit has been underway since 2003 by a joint industry-university team consisting of Garvey Spacecraft Corporation (GSC) and California State University, Long Beach (CSULB).[1] Early concept definition converged on an entirely expendable two-stage launch vehicle featuring liquid propulsion in both stages (Fig. 1). Subsequent interest in a hybrid configuration consisting of a reusable first stage and an expendable manifested itself in the Prospector 7 (P-7) test vehicle. Developed in less than six months under a Phase I SBIR project sponsored by the Air Force Research Lab's Propulsion Directorate (AFRL/RZS), this early low-fidelity reusable NLV (RNLV) first stage prototype was employed to demonstrate rapid turn-around operations in October 2006, with two flights being undertaken in a 3.5 hour period (Fig. 2).[2] It was subsequently adapted to conduct two more flights, with the final one taking place from the Navy's San Nicolas Island (SNI) to pathfind operationally responsive space (ORS) processes at a representative remote launch site.[3]

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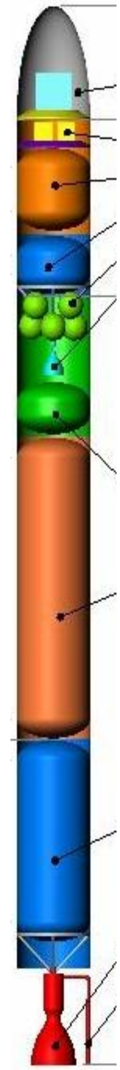
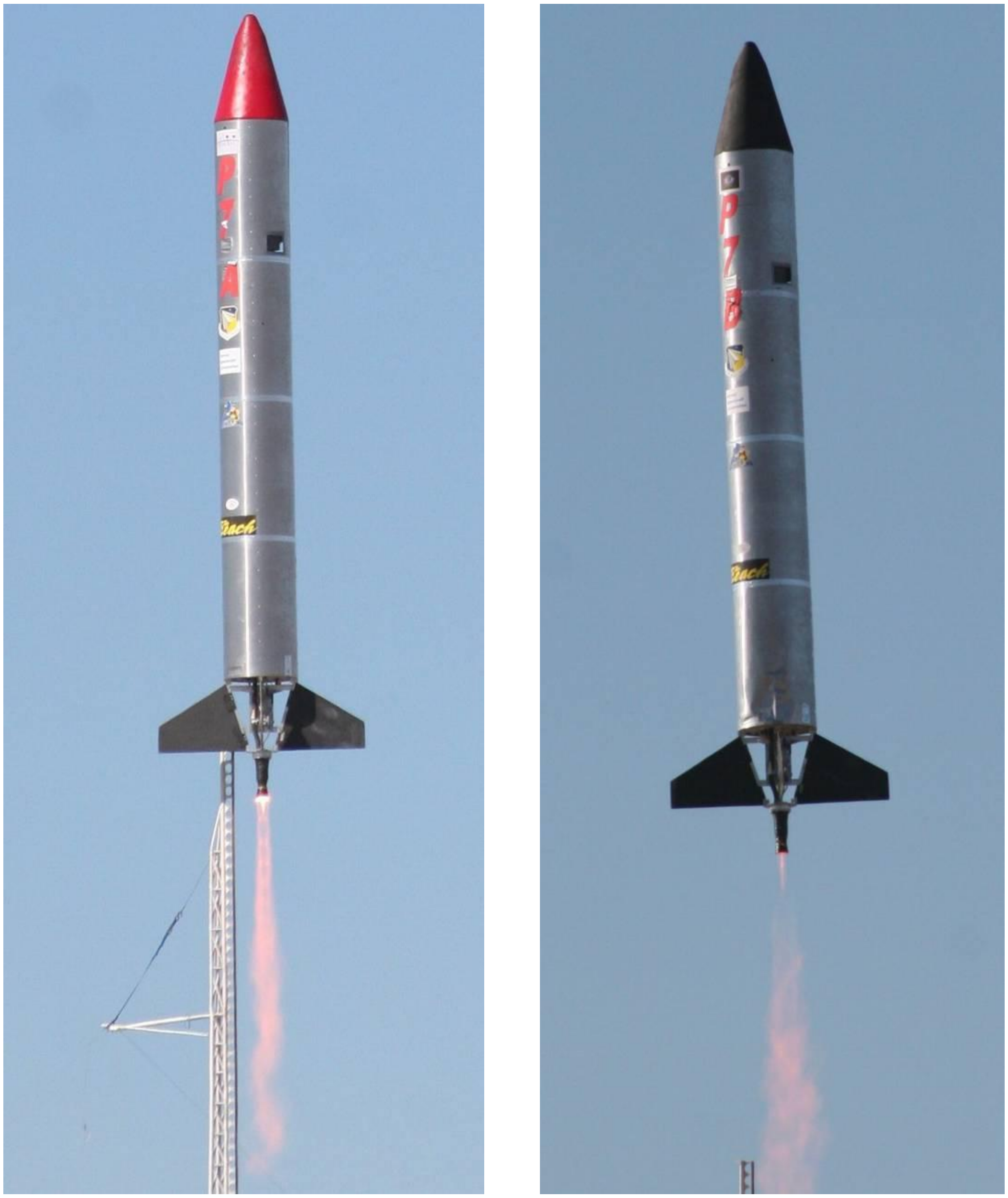


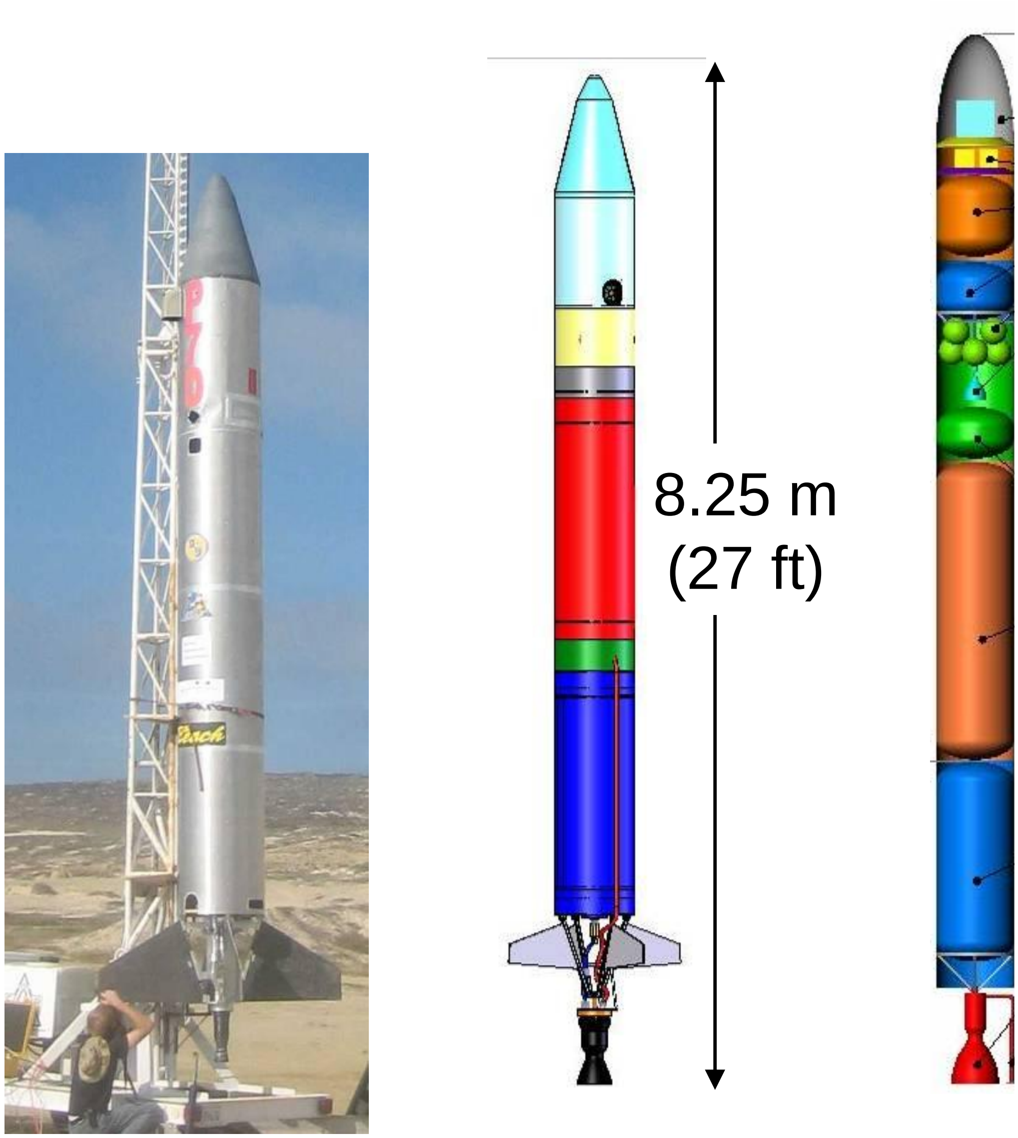
Figure 1. Reference NLV Two-Stage Configuration



P-7A P-7B

Figure 2. Initial Demonstration of Rapid Turn-Around Testing with the Prospector 7

These positive results have enabled the team to continue with a Phase II SBIR follow-on sponsored jointly by AFRL/RZ and the Space & Missile Systems Command (SMC), the objective of which is to improve both the performance environment and operational fidelity of these flights, thereby bringing them closer to those anticipated for orbital missions. The P-7D ORS pathfinder flight at SNI was an early Phase II task for SMC that enabled flight testing to take place right at the beginning rather than having to wait until the very end of the project. Since then, the effort has shifted to developing and testing the follow-on Prospector 9 (P-9) vehicle that has the potential to provide over a magnitude improvement in performance (Fig. 3). The P-9 features a new 4.5 klbf-thrust LOX-ethanol engine, full-scale propellant tanks and avionics that leverage new wireless networking technologies. The propellants tanks from Scorpius SLC (Space Launch Company) are composite and their successful demonstration in flight will enhance their Technology Readiness Level (TRL) to at least a 6.



P-7D **P-9A/B** **NLV**

Integral tanks **Orbital**

Figure 3. The P-7 and P-9 Represent Early Steps in the Incremental Development of an Operational NLV

After the start of the Phase II work, the opportunity arose to leverage and apply some of the P-9 concepts and design to an interim vehicle sponsored by the WIRED (Workforce Innovation for Regional Economic Development) program administered by the California Space Authority on behalf of the U.S. Department of Labor. As discussed below, the Prospector 8 (P-8) served to mitigate technical risk by flying the 4.5K engine and propellant feed system prior to their full-up application on the P-9.

II. NLV First Stage Engine Development

Parametric analysis indicates that a first stage engine with a thrust level on the order of 4.5 klbf will be required for orbital NLV missions, hence its working designation as the "4.5K" engine. While the operational NLV design assumes the use of liquid Oxygen (LOX) and cryogenic propylene as the fuel and some precursor engine tests have been conducted with this combination,[4] the Prospector series of test vehicles have to date primarily featured LOX and ethanol.[‡]

Upon completion of the P-7D flight campaign in the early fall of 2005, priority shifted to developing both the 4.5K engine and an associated test stand for horizontal static fire testing, as documented more fully in Reference 5. Although this engine featured extensive design and fabrication heritage with previous smaller engines, one major change was from a pintle to a flathead injector. Testing got underway in January 2007 with the first successful engine burn following in February (Fig. 4).

Figure 4. Horizontal Static Fire Testing of the 4.5 klbf-thrust First Stage Engine

Subsequent testing identified a problem with the ignition approach when an engine failure occurred after the igniter assembly was prematurely ejected from the chamber. Corrective action consisted of moving the igniters to externally mounting housings, thereby enabling them to fire radially inward across the injector and keeping them out of the path of the incoming propellants. This mechanical change was complemented with refined ignition detection sensing and software-based Go-No Go criteria on whether to then open the main valve assembly (MVA). These improvements have since been validated in multiple static fire and flight test situations.

[‡] A notable exception being the Prospector 14 that utilized LOX and cryogenic methane – the first rocket to do so in a flight environment.

III. Prospector 8

A. P-8 Development and Static Fire Testing

As noted, the P-8 project opened an opportunity to integrate the 4.5K engine and feed system with low-cost propellant tank assemblies derived from heritage designs prior to committing to the P-9. The vehicle also served as a pathfinder for vertical static fire testing, since a new test stand was required to handle the higher thrust levels compared to previous vehicles.

The first static fire test series in June 2007 ended with another major engine failure, this time attributed to propellant leakage across seals within the injector between the LOX and ethanol. Redesigning the injector and fabricating a new one while also repairing the P-8 took two months, with a successful static fire test sequence taking place in August (Fig. 5). Besides validating the corrective actions, these tests also matured the operational procedures needed to ship, handle, load and prepare a vehicle of this class for launch. Furthermore, they provided initial experience with a regulated gaseous Helium (GHe) pressurization for propellant tank pressurization that will be required for high performance missions.

Figure 5. Evaluation of the First Stage Engine and Propellant Feed System During Vertical Static Fire Testing of the P-8

B. P-8 Flight Testing

The P-8 flight test followed the vertical static fire testing one month later in September 2007 from the Koehn Dry Lake Bed outside the town of Mojave, CA (Fig. 6).

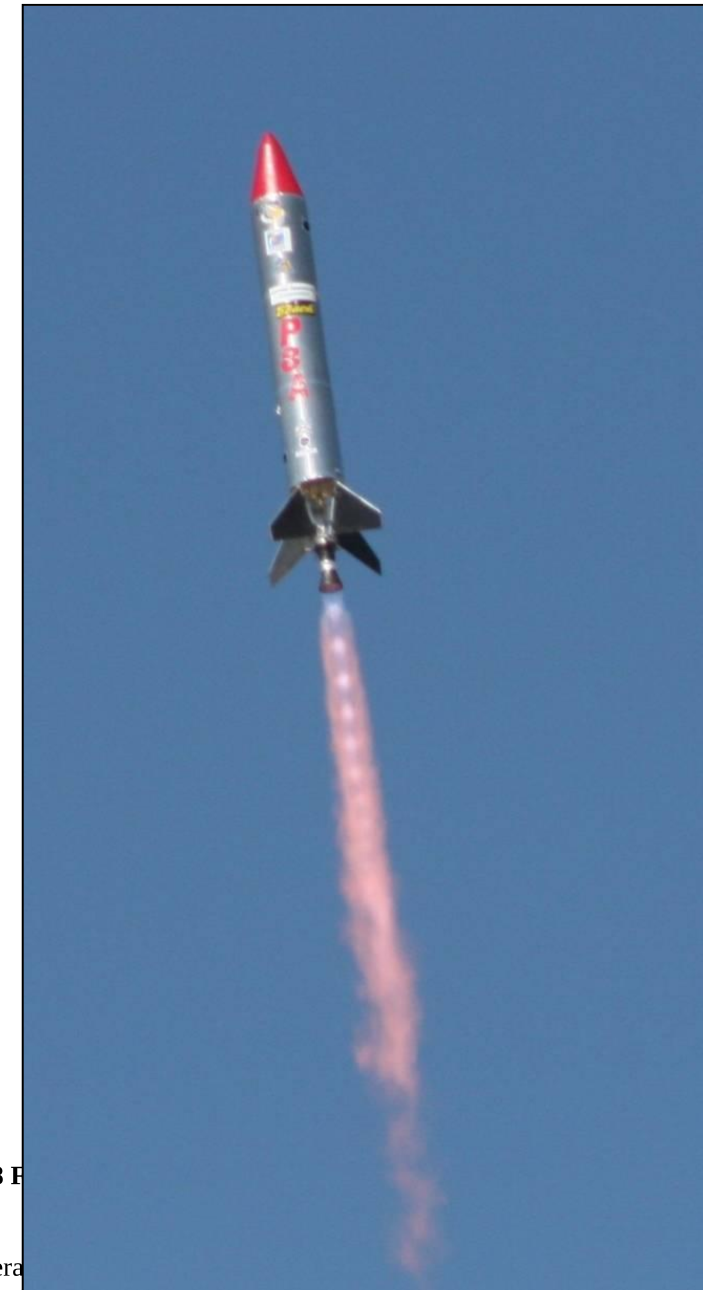


Figure 6. The P-8 F… h Operations

Ignition and the first severa… he propulsion system. However, in order to constrain the maximum altitude to acceptable limits so as to comply with FAA requirements and simplify recovery operations, the propellant tanks were significantly off-loaded from their maximum capability. Consequently, the P-8 thrust-to-weight ratio at lift-off was on the order of 7 g's. The higher velocities and aerodynamic loading relative to previous flight tests caused higher than anticipated fin fluttering, ultimately leading to their structure failure at T+4 seconds (Fig. 7), less than half of the predicted engine burn time.

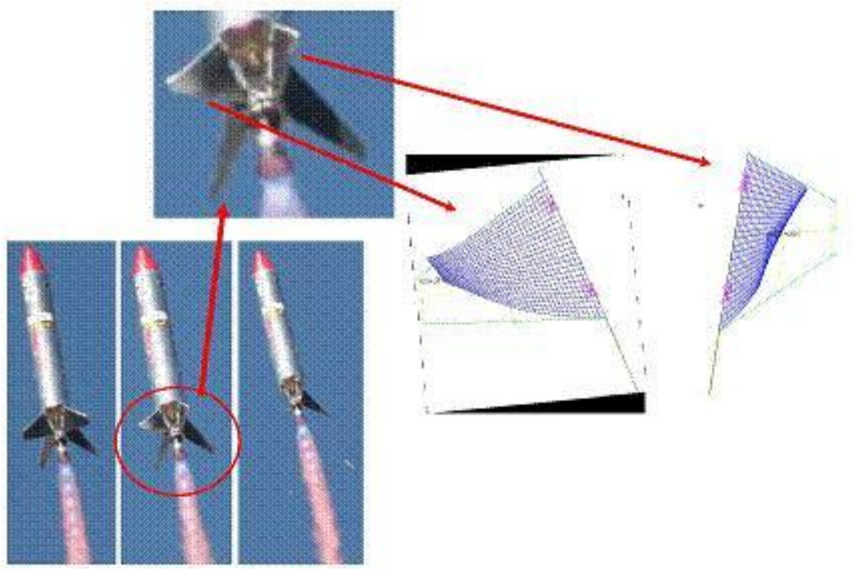


Figure 7. The High Acceleration and Associated Aerodynamic Loading of the P-8 Produced Excessive Fin Flutter

Post-test structural dynamics analysis has determined the principal resonance mode associated with the fin failure and identified redesign options for the fins. Some effort was put into a possible re-flight of a P-8 vehicle incorporating hardware recovered from the flight and redesigned fins, but this option was ultimately shelved in favor of allocating resources into finishing P-9 assembly and integration. Fin structure is not considered to be an issue for operational NLV missions, since fully-loaded vehicles will lift-off with much lower thrust-to-weight ratios (on the order of 1.5 g's) and will either have significantly smaller fins or none at all.

IV. Prospector 9

A. Development, Assembly and Integration

The early Phase II work plan assumed the development of a P-9A/B configuration that would be used to conduct an initial series of low-altitude, rapid turn-around flight operations in the Mojave Desert. This vehicle would have the 4.5 K engine and full-scale propellant tanks, but not yet a functional thrust vector control system or regulated GHe propellant tank pressurization system. These would be added after the rapid turn-around demonstrations to create the P-9X configuration for a high performance, more ambitious ORS-oriented flight attempt at SNI.

These plans have evolved over the course of the Phase II effort in response to both growing programmatic requirements and the consequences of the previously noted failures during field testing. Regarding new requirements, SMC has elected to add a new GPS/IMU experiment from NASA to the P-9, making it a primary payload in contrast to the numerous secondary payloads that are routinely manifested on these flights.[§] Cost-containment mandated by corrective actions include the indefinite postponement of the addition of the thrust vector control and the tank pressurization system to create the P-9X, as well as the associated SNI flight test.

While these programmatic actions were underway, P-9A/B assembly accelerated during the fall of 2007. By the end of the year, the composite propellant tanks were integrated with the intertank, equipment bay and thrust structure (Fig. 8). Figure 9 shows the initial integration of this first stage with the interstage and fairing in the lab on the CSULB campus, while Figs. 10 and 11 are close-ups of the P-9 MVA within the thrust structure and various assemblies within the intertank, respectively.[**] Overall, the P-9A/B is forecasted to have dry mass at launch of 696 lb, and a gross lift-off weight of 948 lb[††], versus 378 lb and 3400 lb for an operational NLV.

[§] For the P-9A/B, these include the RocketPod CubeSat deployer from Ecliptic Enterprises, and a number of wireless sensor experiments provided by NASA Johnson Space Center.

[**] The term "interstage" is retained for the vehicle element between the first stage and fairing to retain commonality with the full-up NLV that will also feature this unit between the first stage and a second stage.

[††] In order to stay within the range limits, the propellants tanks are loaded only at 13% of their capacity

Figure 9. Initial Assembly of the P-9 Vehicle in the Aerospace Systems Lab at CSULB

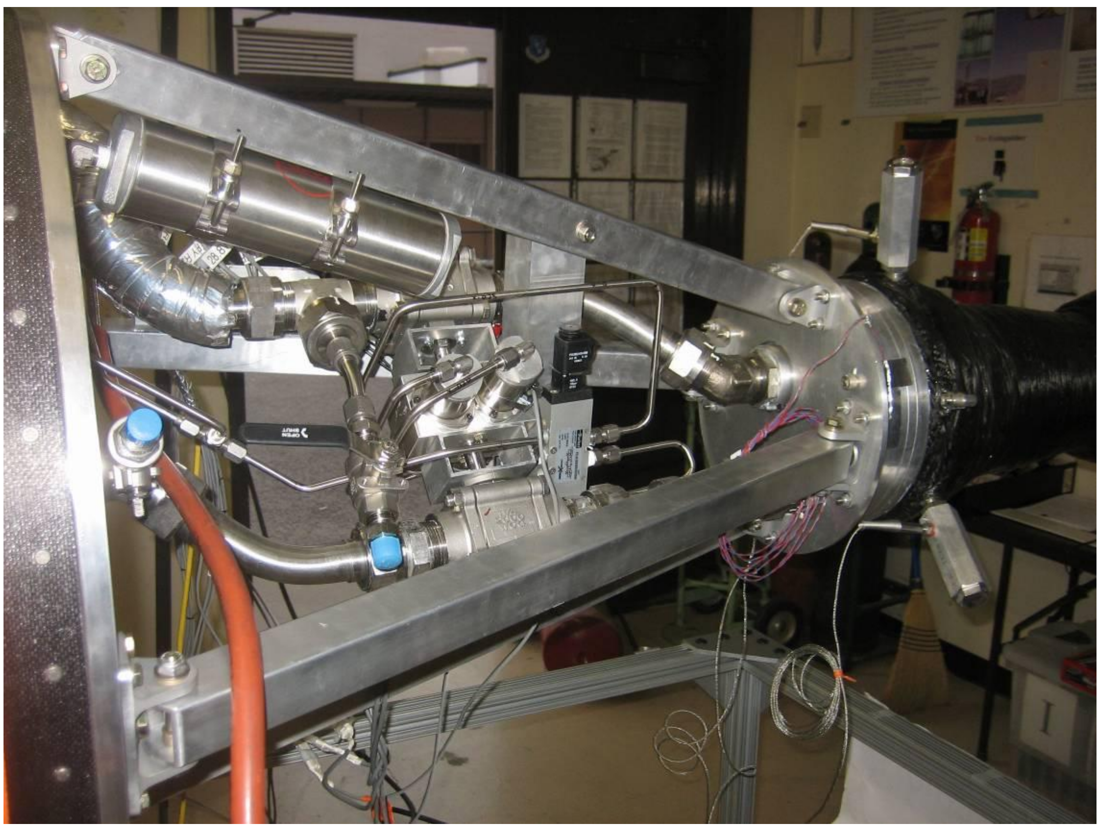


Figure 10. Main Valve Assembly Mounted on the Thrust Structure

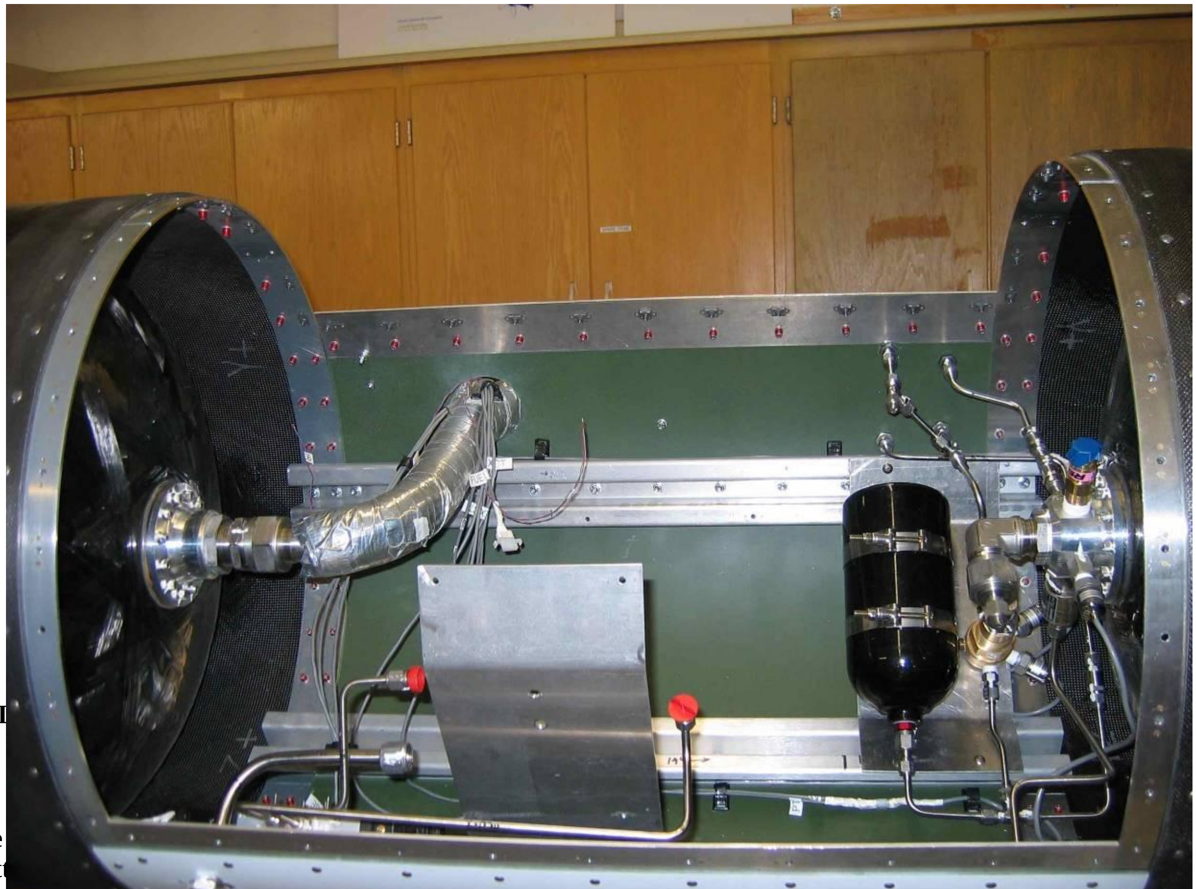


Figure 11. I

B. Static Fire

The first at

of the procedures and equipment first used on the P-8 vertical static fire tests as well as many of the ensuing lessons learned. Progress included the first loading and loading of propellants (Fig. 13) and evaluation of the instrumentation telemetry system based on commercial wireless products. However, at T-0, after energizing the igniters (Fig. 14), the main valve assembly froze up and failed to open (Fig. 15).

Figure 12. P-9 on the FAR Large Vehicle Test Stand

Figure 13. LOX Tank Loading Underway

Figure 14. Igniters Energized at T-0 seconds

Figure 15. MVA LOX Ball Valve that Failed to Open

Post-test inspection has determined that excessive tolerances in the alignment of the actuator shaft and ball valves created too much resistance for the actuator to overcome under cryogenic conditions. Corrective actions are to tighten alignment tolerances and for additional margin replace of the existing actuator with the next larger available size. Furthermore, the ball valves are now inspected, cleaned and rebuilt after delivery from the supplier and the entire MVA is undergoing cryogenic acceptance testing with liquid nitrogen prior to final installation in the vehicle. These techniques have been partially validated in other vehicles that have MVA that share design features with that of the P-9.

C. Flight Test Plans

Following the completion of the first static fire test and failure investigation, final P-9 assembly and integration went into standby mode while waiting for execution of a small enhancement follow-on phase. Open items include completion of the main parachute recovery system and the modified MVA and delivery and integration of the SMC / NASA GPS/IMU experiment. The enhancement was implemented at the end of May and consideration is now

being given to a late July or August flight test. However, given the extreme temperatures at that time of year, there is a distinct possibility that these tests could be pushed back to early fall.

V. Future Plans

There is presently no clearly defined follow-on defense-related opportunities for the design and capabilities that the P-8 and P-9 series of test vehicles present. In particular, water-based recovery of the first stage on high performance missions – as simulated during testing in Long Beach Harbor in late 2007 (Fig. 16) – does not come under the scope of those concepts addressed in recent Responsive Access to Space Technology Exchanges hosted by AFRL's Air Vehicle Directorate. In parallel, ORS launch requirements now appear to favor larger payloads that are far beyond the capabilities of an NLV.

Figure 16. Preliminary Simulations in Long Beach Harbor Indicate that Ocean-based Vehicle Recovery Merits Further Consideration for Reusable Systems

In contrast, the GSC/CSULB team is pursuing several opportunities to support NASA technology development and mission objectives. The first of these involves the flight testing of wireless sensor and networking technologies on the Prospector 11, which is a refined version of the P-8. The other is the conversion of the P-9 design to conduct near-term LOX-methane flight tests. These would build upon the experience that the team has gain through the first-ever flight test of this propellant combination that took place with the Prospector 14 in April of this year (Fig. 17).[6] Elevating the TRL of this propulsion technology to a 6 or even 7 for both first and second stage applications could be a key factor in validating its maturity for use in a future lunar lander ascent stage.

Figure 17. The P-9 Configuration is Readily Adaptable to LOX-Methane, the First Flight of Which was Achieved with the Smaller Prospector 14 in April 2008

VI. Conclusion

This project has already achieved significant milestones in the development and flight demonstration of key technologies, systems and operations that are required to implement operational reusable launch vehicles. Even before completion of the next phase of flight testing with the advanced P-9 prototype, the challenge is transitioning to maintaining the momentum to continue refining the first stage configuration, develop an upper stage, expand the flight test envelope to high altitudes and ultimately conduct NLV-based missions that routinely deliver nanosat-class payloads to low Earth orbit.

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